Course Name: Design of Electric Motors

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Title: Procedure for Calculation of SRM Inductance: Aligned Inductance -1

Greetings to all, in this lecture we will discuss the analytical calculations of switched reluctance machine inductances like in aligned position what will be the inductance, unaligned position what will be the inductance and intermediate positions from aligned to unaligned or unaligned to aligned position what will be the inductances based upon the simple MMF's and inductances equations we will derive in detail. First we will see what will be the flux lines and flux plot related to the aligned position, unaligned position and intermediate positions. Here we can see the flux plot with respect to the aligned position of switched reluctance machine as per the excitation. If we will excite this windings, these windings if we will excite then rotor pole will aligned with respect to the excited winding based upon the lower reluctance principle as well as the electromagnetic attraction principle. The flux line plot with respect to the FEMM simulation we can see here and to make the analytical calculations of the inductance I have drawn the theoretical way of representation. Here we can see the flux lines in the pole places the flux lines are in parallel with the pole axis.

Here we can see these are the flux lines which are deviating with respect to the reluctance. So, these things are neglected and considered that as a concentric circles in the rotor back iron. We can see the same thing here. So, at the rotor back iron I consider the flux lines as a concentric circles in the stator pole as well as rotor pole.

I consider the flux lines are in parallel with respect to the pole axis and similarly in the rotor sorry stator back iron the flux lines are concentric circles. Even though in the simulations we are seeing little bit deviation in the flux lines depends upon the reluctance for analytical calculations we are assuming the flux lines in the back iron stator as well as rotor back iron will be concentric circles and stator and rotor poles will be parallel to the pole axis and maximum flux lines are flowing in the low reluctance path that is this one. And leakage flux lines we can see here small circles very less magnitude of leakage flux is there in this position. Next we will see the flux line plot with respect to the unaligned position. So, in unaligned position with respect to the FEMM simulation the flux lines are in this manner.

So, here also the assumptions are in the rotor back iron as well as stator back iron the flux lines are represented with concentric circles for analytical estimation of flux line path as well as inductances. And different flux loops I have considered here for analytical calculations similar to the actual flux distribution with respect to the FEMM simulation. And these are the flux line distribution from aligned position to unaligned position that is 0 degree to 22.5 degrees theta variation and with a step of 5.625 degrees we can see this is the aligned position if you will rotate the rotor 5.6 degrees then it will be in this manner then next 5.6 degrees it will come in this fashion next 5.6 degrees it will come in this manner and like this after this position it will be completely unaligned condition and we will see the similar kind of flux lines. So, we will consider this flux lines how the flux lines are flowing in various cases case 1 aligned condition and case 2 unaligned condition and case 3 intermediate condition based upon this flux lines actual flux lines we will make the analytical flux plot and each and every flux line we will calculate the what is the length and what can be the reluctance and based upon that thing we will calculate the inductance values. So, first we will see the procedure to find the inductances for all these three cases.

As per the magnetic circuit analysis the mmf N into I is equals to flux divided by magnetic capacitance that is what we have derived during magnetic circuit analysis lectures and it is also equals to flux into reluctance mmf N into I.

So, this is equation 1 and as per the faraday's law we have derived the expression for inductance N into phi is equals to L into I that is flux linkages here L is equals to N into phi divided by I. So, this equation we will utilize to calculate the inductance in all three cases.

So, for calculating this inductance value based upon this equation we require the flux with respect to the different cases what will be the flux and what is the flux path and different reluctance also. So, here the reluctance is equals to length divided by permeability of the magnetic material or medium into area of cross section and units are 1 by henry and this is the reluctance value.

So, flux is nothing but mmf by reluctance from the equation 1. We can see here based upon the equation flux is nothing but mmf by reluctance based upon this equation we can calculate the flux and this flux value we have to substitute in equation number 3 then we can find the inductance value this equation number 4 and equation number 5.

So, based upon this phi set of equations we will calculate the inductances with respect to all three cases that is aligned unaligned and intermediate positions. So, first we will discuss the procedure what are the steps we have to follow step 1 as per the flux plot. So, this is the flux plot with respect to aligned condition.

So, we have to identify the number of flux paths or flux regions let us say this is the actual flux part and this is the analytical calculation based flux plot here this flux loops with respect to the stator back iron are symmetrical in semicircular manner. So, this is one loop and this is the leakage flux with respect to the other side is second loop. So, this is loop 1 and loop 2 with respect to the symmetry I am dividing the complete flux part based upon this flux number of flux paths we have to calculate the inductances. For aligned condition the number of flux plot flux paths or flux regions I am considering two let us insert the aligned condition flux plot. So, this is the aligned condition flux plot.

So, this part is region 1 and the leakage flux 1 that is this circle is nothing, but region 2. So, we will we have identified these two regions and with respect to these two regions we will calculate the inductances. Identify the number of flux paths or regions and step 2 find the length of magnetic flux path let us say this is the in region 1. So, this is the region 1 right. So, with respect to the region 1 what is the magnetic flux path length the flux lines are flowing through the stator back iron and then stator pole rotor pole and then stator rotor back iron and then rotor pole and stator pole back to the stator iron.

So, we have to find the length of flux path and here in step 1 the number of flux paths or number of regions we have to represent with n, n is nothing, but a variable that is representing the number of flux paths or regions. And step 3 we have to find the cross sectional area with respect to the flux lines flow. Similar to the magnetic circuits analysis here also the perpendicular area with respect to the flux lines flow we have to calculate area of cross section. And step 4 we have to find the we have to draw the magnetic equivalent circuit and we have to calculate the reluctance based upon the network theory analysis reluctance is equals to l by mu a length divided by permeability into area of cross section. So, final reluctance value effective reluctance value with respect to each flux loop we have to calculate.

And step 5 we have to calculate the inductance with respect to the different flux loops. So, inductance is equals to n into 5 divided by I. So, here flux we have to calculate based upon the mmf divided by with respect to the equation number 5 mmf divided by reluctance.

And step 6 here with respect to the n number of flux loops L is equals to L j we will represent that is equals to n into n is nothing, but number of flux loops n into n 5 divided by I. Let us say with respect to the aligned condition if I want to calculate the flux inductance with respect to the region 1 means.

So, semicircles if I will consider the in region 1 I can calculate the flux path with respect to the one side and other side also same flux path is there right. So, this loop is same as well as this side loop also same. So, two paths are there. So, here n is representing similar number of flux loops how many number of similar flux loops are there with respect to that particular region. And in step 6 we have to find the effective inductance with respect to the aligned or unaligned or intermediate position L effective is equals to sigma j equals to 1 to x L j.

So, here x is equals to number of flux paths or regions which we have defined in step 1. Step 1 I think I represented with n right. So, this should be as a variable x. So, x is representing the number of flux paths or regions. So, based upon the number of flux paths we have to calculate the effective inductance in terms of summation.

So, first we will calculate the inductance with respect to the aligned condition and unaligned condition and intermediate position we can follow the same procedure to calculate the inductance. Let us consider the aligned condition flux line plot and with respect to the excitation flux lines are flowing in this fashion and here the assumptions are during with respect to the stator back iron and rotor back iron here in this place and in this place we are assuming flux lines are concentric circles in the stator pole as well as rotor pole. This stator pole and here rotor pole the flux lines are parallel with the pole axis and maximum flux lines like 90 to 98 percent of the flux lines are flowing through the stator pole and rotor pole and leakage flux we can see here these are the small circles. This one is the leakage flux small circles and this leakage flux is very small. So, with respect to the procedure we will calculate the inductance in aligned condition.

So, step one we have to identify the number of flux paths. So, path one I am considering with respect to the this green color flux lines this is region one and the leakage flux path I am considering region two. This is based upon the assumptions only I am considering region one as first case and region two as second flux path. So, path one is with respect to stator yoke or stator back iron to stator pole and stator pole to air gap air gap to rotor pole then rotor yoke then rotor yoke to again rotor pole then rotor pole to again air gap air gap to stator pole and then finally, stator yoke again. So, with respect to the region one the flux lines are flowing with respect to this path and then next path two the flux lines are flowing that is leakage flux this small circles this one this circle and this circle and bottom side also here and here these are the leakage flux path that I am considering as path two.

So, that is stator yoke or stator back iron to stator pole then air gap with respect to stator pole sorry stator slot it will be. So, in this region the leakage flux lines are flowing right this circle small circle. So, this is the leakage flux path after that thing it is coming back to stator yoke we can observe from here from this plot. So, flux lines are flowing from stator yoke to stator pole and then back to slot region stator slot region that is I am considering as air gap and then back to stator yoke. So, with respect to these two flux paths we have to calculate the inductance first I will consider the path one.

So, with respect to the path one I will calculate the inductance then with respect to the path two I will calculate the inductance and at the end I will add both inductances. So, with respect to the path one apply the step two find the length find the length of magnetic flux path. So, with respect to this aligned condition and region one what will be the flux path l equivalent is equals to flux path is written here. So, based on that thing length of stator yoke plus two times the length of stator pole plus two times the length of air gap plus two times the length of rotor pole plus length of rotor yoke. How I have written this equation we can see from this path stator yoke is coming to one time this is like in a symmetrical manner if I will consider stator yoke will be starting point and ending point it is same and stator pole we are seeing two times and rotor pole also two times the flux lines are flowing through the rotor pole here also rotor pole and then rotor yoke is one time and air gap also two times we can we can observe same thing here.

So, flux lines are entering here stator pole air gap then rotor pole and rotor yoke or back iron and then rotor pole here rotor pole and then air gap. So, then stator pole and this is once the stator yoke. So, like this flux loops are two are there at the end we will multiply the inductance into two times with respect to path one. So, this is the effective length of the path with respect to this flux path or flux loop. Next we will calculate the length with respect to the different parts of the flux loop.

So, first length of the stator yoke length of the stator yoke flux path in this region from this point to this point what will be the length of flux path mean length of the flux path with respect to this complete region we have to consider. So, mean length will be with respect to the outer diameter that is pi D by 2 right pi into D naught s by 2 plus with respect to the inner diameter with respect to the stator yoke will be this radius right. We can see here it should be with respect to this radius right the blue color line we can see here. So, that is nothing but pi into D naught s minus 2 into dcs dcs is nothing but depth of this stator back iron by 2. So, this is the length of the flux path with respect to the outer diameter and inner diameter with respect to the stator pole that is this one.

So, then finally, we have to consider the mean then we will get the pi by 2 final equation pi by 2 into D naught s minus 2 D naught s minus dcs this is the length of the flux path in stator yoke.

And same way we can calculate the length of the stator pole in stator pole length will be same right this is the stator pole length stator pole length will be equals to pole height that is dss. And air gap length will be is equals to lg equation number 6 and equation number 7. And then length of the rotor pole is equals to length of the rotor pole height from this point to this point what will be the length that is nothing but dsr rotor pole height.

And then length of the rotor yoke length of the rotor yoke again from this point to this point we have to calculate the mean mean length of the magnetic flux path this is the region. So, in this region we have to calculate the mean length of the magnetic flux path. So, inner diameter will be pi into Dir by 2 plus this is with respect to this part we can see with respect to this part it will be pi Dir by 2 with respect to this one that is pi into D naught r minus 2 into dsr by 2 D naught r is nothing but outer diameter of the rotor and dsr is nothing but thickness of rotor back iron. And finally, we have to consider the mean this equation will give you the length of the rotor yoke flux path pi by 4 into Dir plus D naught r minus 2 into dsr sorry here dsr will be pole height. So, we are calculating from the D naught r right. So, this diameter rotor outer diameter will be D naught r minus this distance we are subtracting then we will get the mean diameter with respect to the pole rotor pole bottom side that is this red color one.

So, finally, we have to do the mean. So, this is equation number nine. So, after calculating the length in step three we have to calculate the area cross sectional area with respect to all this flux paths this is flux path one in region one. So, each and every section what will be the area for example, a cross sectional area with respect to the stator yoke region is equals to. So, this area we have to calculate cross sectional area in perpendicular direction with respect to the flux flow that is dcs into length of the stator core or length of the core this is cross sectional area of the stator yoke. Next cross sectional area of the stator pole is equals to we have to see perpendicular area with respect to this one.

So, perpendicular area with respect to this blue color highlighted one is nothing, but x axis length into y axis length if we will say width of the stator pole will be wsp into length of the stator core that will give the area of cross section. Then same way length of the cross sectional area of the air gap already we have calculated beta s into Dis by 2 into le this is simply r into theta arc length we are getting in this air gap region what will be the area. So, this arc length is nothing, but r into theta into le will give you the area with respect to the air gap and then area with respect to the rotor pole is this one perpendicular cross sectional area with respect to the flux line flow. Same way rotor yoke this all parameters we are calculating with respect to the flux path one right that is why one subscript I am adding Ary is equals to this is the area we have to calculate perpendicular length will be x axis length will be dcr that is thickness of the rotor back iron dcr into length of the core. So, these are the area of cross sectional area of the flux lines with respect to path one is equation number ten.

Next with respect to the step four we have to analyze the equivalent circuit of equivalent magnetic equivalent circuit with respect to the path one. We can see this is the region one. So, this is the region one right. So, with respect to the region one. So, the mmf will be f by 2 here at the top side half of the number of turns are placed that is F by 2.

Then magnetic capacitance with respect to the stator pole Cmsp one, then magnetic capacitance with respect to the air gap, magnetic capacitance with respect to the rotor pole, magnetic capacitance with respect to the rotor yoke and magnetic capacitance with respect to again rotor pole, magnetic capacitance with respect to air gap and then magnetic capacitance with respect to stator pole. Then in series with that again half of the mmf is there, this is f by 2 and then magnetic capacitance with respect to the stator yoke Cmsy1. So, this is the equivalent magnetic equivalent circuit with respect to the flux path one and here d phi by d t is the flow variable that is Im is equals to d phi by d t with respect to the flux path one, we can represent with d phi 1 by d t. So, here magnetic capacitance Cm is equals to 1 by reluctance. So, effective like effective equivalent circuit we can draw in this fashion.

So, the effective mmf will be f that is N into I and equivalent capacitance will be this thing and here flow variable will be d phi 1 by d t. So, similar to the magnetic like electrical circuits analysis or network theory analysis, here we can calculate the equivalent magnetic capacitance that is equals to 2 times the magnetic capacitance with respect to the stator pole and 2 times the magnetic capacitance with respect to the air gap 2 and then only one time the magnetic capacitance with respect to the rotor yoke and 2 times the magnetic capacitance with respect to rotor pole plus 1 by magnetic capacitance with respect to the stator yoke also one time. So, this is equation number 13 sorry this will be equation number 11 and this is 12.

So, after knowing this thing m m f is equals to flux by magnetic capacitance right magnetic capacitance this is equation number 13 in terms of reluctance if you will write that is mmf is equals to flux into reluctance this equation number 14 and if you will write the equivalent capacitances in terms of reluctance because Cm is equals to 1 by reluctance right. So, equivalent reluctance is equals to 2 times the reluctance of stator pole plus 2 times the reluctance of air gap plus one time reluctance of rotor yoke plus 2 times the reluctance of rotor pole plus reluctance of stator yoke this is equation number 15.

So, here we have based upon this reluctance equation we can find the flux, flux phi 1 is equals to with respect to the path 1 mmf divided by reluctance right equivalent reluctance with respect to path 1 this is equation number 16.

So, we have to calculate the reluctance then we can find the flux with respect to the path 1. So, reluctance with respect to the stator pole is equals to length of the stator pole divided by permeability that is mu naught and mu r into area of stator pole and same way reluctance with respect to the air gap lg divided by mu naught because it is air gap there is no mu r and area of cross section with respect to the air gap same way we can calculate the rotor yoke reluctance and reluctance with respect to the rotor pole reluctance with respect to the stator yoke this is equation number 17.

So, finally, after calculating the reluctance as per the step 5 the inductance is equals to number of similar flux loops in path 1 with respect to path 1 into n phase into phi 1 divided by I here we can see from the flux plot with respect to the aligned condition this is the region 1 we are we have considered right.

So, like this flux loops we have 2 right. So, this is 1 loop and this side another loop is there ok. So, 2 loops are there orange color line you can see. So, here n is equals to 2. So, l aligned condition inductance in aligned condition with respect to the path 1 is equals to 2 times the n phase number of turns per phase into phi 1 divided by I here phi 1 we have to calculate with respect to this equation number 16.

So, aligned inductance with respect to the region 1 or flux path 1 we can see here next we have to calculate the inductance with respect to the flux path 2 that is leakage inductance this is this small circles.

So, this is the flux path with respect to the leakage fluxes. So, here 4 loops are there n equals to 4 here. So, this thing we will discuss in the next lecture with this I am concluding this lecture in this lecture we have discussed the inductances with respect to the various positions of the rotor like aligned condition, unaligned condition and ah intermediate condition how to calculate the inductances detailed procedural steps we have discussed the calculations we will continue in the next lectures also. Thank you.